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AFOSR-TR-97

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1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE 2/18/97	3. REPORT TYPE AND DATES COVERED Final Technical Report 4/1/95-10/31/96	
4. TITLE AND SUBTITLE 'Contoured Holes for Film Cooling: the Effect of Kidney-Shaped Vortices'		5. FUNDING NUMBERS F49620-95-1-0273	
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9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) AFOSR/NA 110 Duncan Avenue, Suite B 115 Bolling Air Force Base DC 20332-8080		10. SPONSORING / MONITORING AGENCY REPORT NUMBER	
11. SUPPLEMENTARY NOTES		19971002 145	
12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution unlimited.		12b. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200 words) Flow visualization studies were carried out in water to ferret out the fluid dynamical mechanisms underlying the shaped holes used in film cooling. Both laser induced fluorescence and particle image velocimetry were used. The results uncovered two fundamental reasons why shaped holes work. First, by proper shaping of holes, one can increase the lateral separation of the kidney-vortices: this delays the lift off of coolant jets. Second, some shaped holes are found to be conducive to what we call an anti-kidney pair, whose sense of rotation is opposite to that of the kidney pair. The anti-kidney pair, the presence and the formation mechanism of which appears to be first identified in this study, has also the undesirable effect: it entrains the hot crossflow into the central region of the jet and toward the surface. However, if the anti-kidney pair is properly positioned so that it can cancel the adverse effect of the kidney-pair, then the anti-kidney pair can prevent the jet lift-off. Thus the very key for the improved design of shaped holes is the manipulation of the hole geometry in such a way that the kidney and anti-kidney vortices annihilate each other.			
14. SUBJECT TERMS Aircraft Gas Turbines, Film Cooling, Shaped Holes		15. NUMBER OF PAGES 8	
		16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT

1. **Title** "Contoured Holes for Film Cooling: the Effect of Kidney-Shaped Vortices"
2. **Overall Objective** Improve film cooling effectiveness of shaped holes used in turbine cooling by confirming the predicted presence of anti-kidney vortices and exploiting them to cancel the adverse effect of kidney-vortices
3. **Grant Number** F49620-95-1-0273
4. **P.I. and Graduate Student** M.Kurosaka, P.I. and Professor; Major Brenda A. Haven
5. **Organizations and Address** Department of Aeronautics and Astronautics
University of Washington, Seattle, WA 98195-2400
6. **Starting Date** April 1, 1995
7. **Ending Date** October 31, 1996

8. Summary Description of the Entire Program

The need for improved turbine blade cooling performance has led to the advent of "shaped" holes. These cooling hole designs are characterized by an increase in cross-sectional area toward the exit, and by cross sections departing markedly from round holes. At higher blowing ratios, which are based on the coolant inlet velocity, the film cooling effectiveness of the shaped hole is higher than that of the round hole. This benefit of shaped holes has been conventionally attributed to the reduction in coolant exit velocity caused by the increased hole exit area. Although this is certainly true, it appears to be only a part of the answer. Even when we adjust the blowing ratio to account for the reduction in exit velocity, the film cooling effectiveness of the shaped holes remains higher. Efforts to overcome these drawbacks are thwarted by this lack of additional fluid dynamical mechanism of why shaped holes work.

In general, in film cooling jets, a pair of counterrotating vortices are formed as the coolant jet interacts with the oncoming hot gas stream. As shown in figure 1, these vortices, often referred to

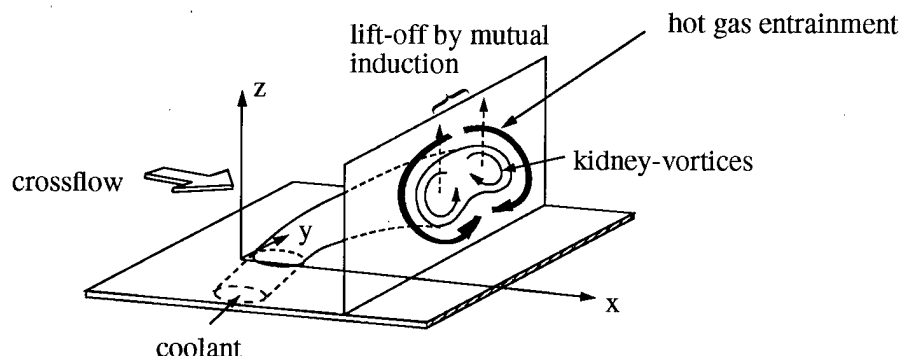


Figure 1. Kidney-Vortices formed by a Jet in a Crossflow

as “kidney-shaped” vortices, or kidney-vortices, have a sense of rotation that acts to lift the coolant from the surface. As the coolant leaves the surface, the rotation of the vortices also promotes entrainment of the hot gases down toward the surface. The combination of coolant lift-off and hot gas entrainment can seriously degrade the effectiveness of the film cooling layer.

In this study based on flow visualization, we identified two additional mechanisms at work for shaped holes, both of which can lessen the detrimental effects of the kidney-shaped vortices. First, by the proper shaping of the holes, one can increase the lateral separation of the kidney-vortices. The increased width reduces the mutual induction between the kidney-vortices (see Fig.2) and delays the jet lift-off.

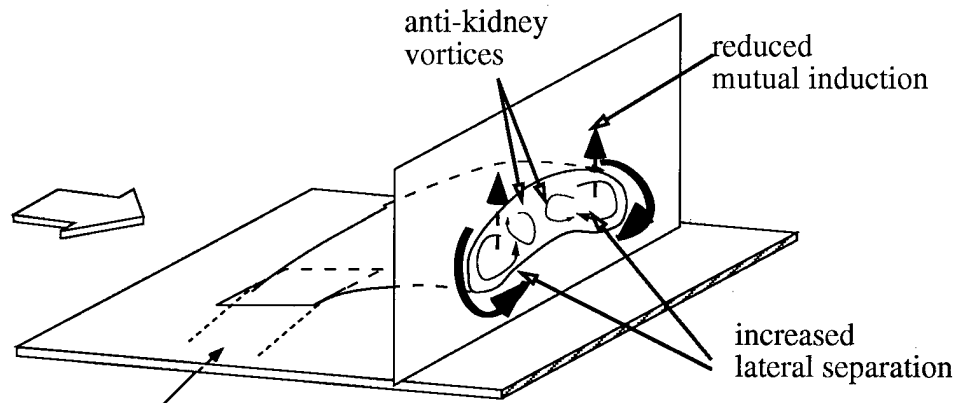
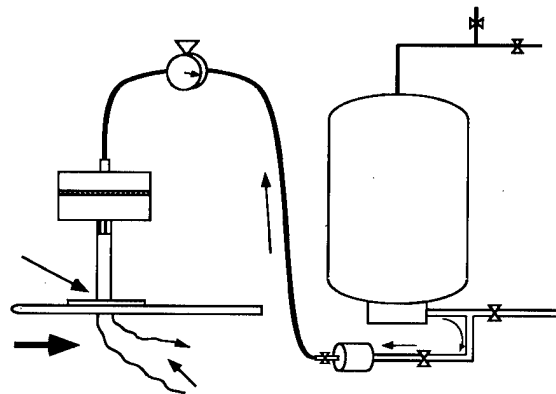


Figure 2. Benefits of Shaped Holes

Second, some shaped holes are found to be conducive to generating what we call an anti-kidneypair, whose sense of rotation is opposite to that of the kidney pair. The anti-kidney pair, the presence and the formation mechanism of which appears to be first identified in this study, has also the undesirable effect: it entrains the hot crossflow into the central region of the jet and toward the surface. However, if the anti-kidney pair is properly positioned so that it can cancel the adverse effect of the kidney-pair, then the anti-kidney pair can prevent the jet lift-off.

Both experimental and analytical methods were used. The experiments using laser induced fluorescence and particle image velocimetry techniques were carried out in a water tunnel. Jets are injected normal to the crossflow as shown in figure 3. Six simple hole geometries were studied: low-aspect ratio rectangle (hole 1), low-aspect ratio ellipse (hole 2), round (hole 3), square (hole 4), high-aspect ratio ellipse (hole 5), and high-aspect ratio rectangle (hole 6).



Heuristic analytical models were constructed to understand the formation mechanism of anti-kidney pair. The results from these basis studies are found to shed light on the jet behavior and on actual air data obtained by industry for practical shaped film cooling holes. For details, see Haven (1996).

10. Results/New Findings

[10-a] Lateral separation of kidney-shaped vortices

According to the common view, kidney-vortices are the downstream manifestation of vorticity initially arising from within the side-wall boundary layer of the hole passage. As illustrated in figure 4 for rectangular holes, the side-wall of the hole generates vorticity aligned with the x-direction. This vorticity then shows up in a laser sheet oriented in the y-z plane as the kidney-vortices.

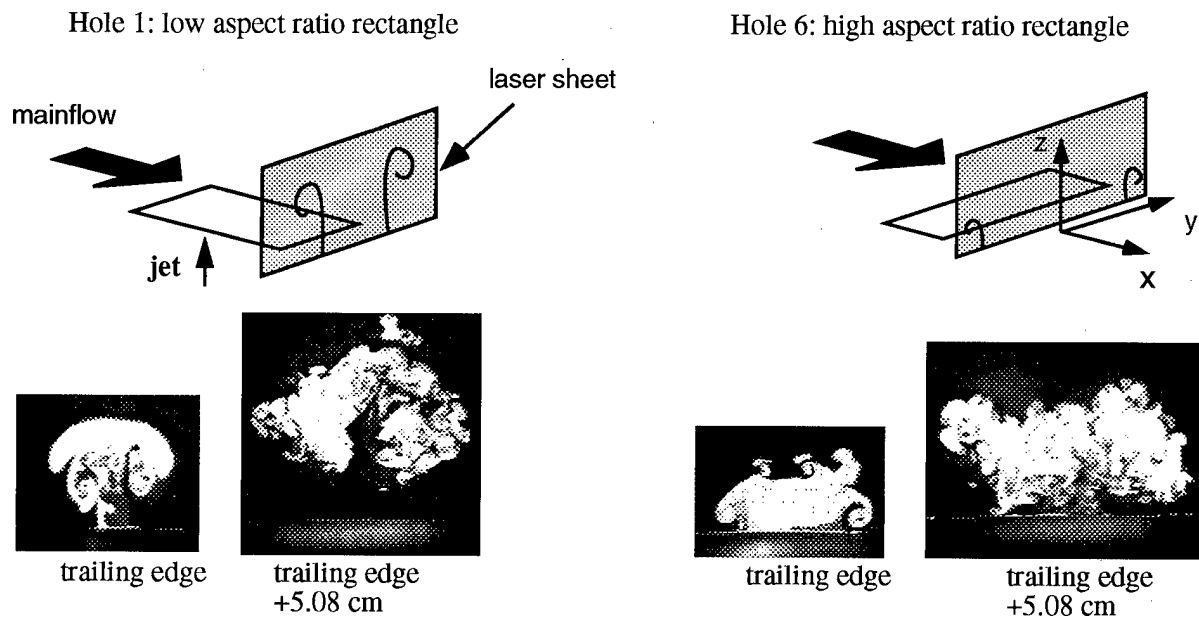


Figure 4. Effect of hole geometry on lateral separation of kidney vortices

When we focus only on the vorticity generated by the side-wall of the hole, it is reasonable to expect that the lateral separation of the kidney-shaped vortices can be manipulated by changing the hole geometry: even for the same cross-sectional hole area, the larger the cross-stream dimension of the hole, such as in the case of hole 6, the larger the lateral distance separating the kidney-shaped vortices. The increased separation decreases the mutual induction due to the vortex pair; the net result is that the jet tends to stay near the surface. On the other hand, as the kidney vortices

are brought closer by decreasing the cross-stream dimension, as in the case of hole 1, the mutual induction increases and the jet lifts off the surface. Figure 4 indeed substantiates this expectation.

By proceeding along this line of reasoning, we came up with the prediction for the 'spectrum of shaped holes' displayed in figure 5 for all holes .

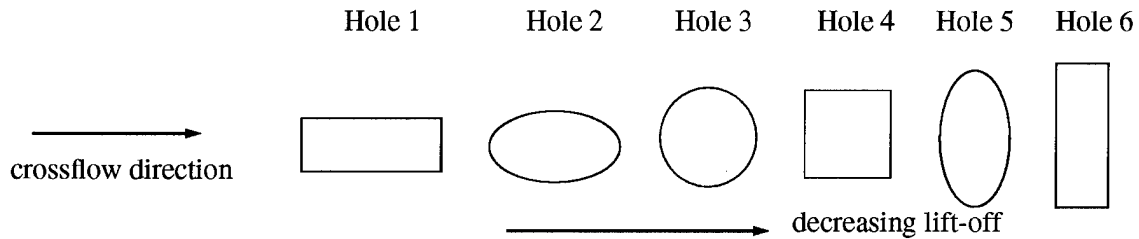


Figure 5. The trend between side wall curvature and the jet lift-off

Note here that the cross-sectional areas of all holes are the same. The confirmation of the predicted trend for all the holes is shown in figure 6.

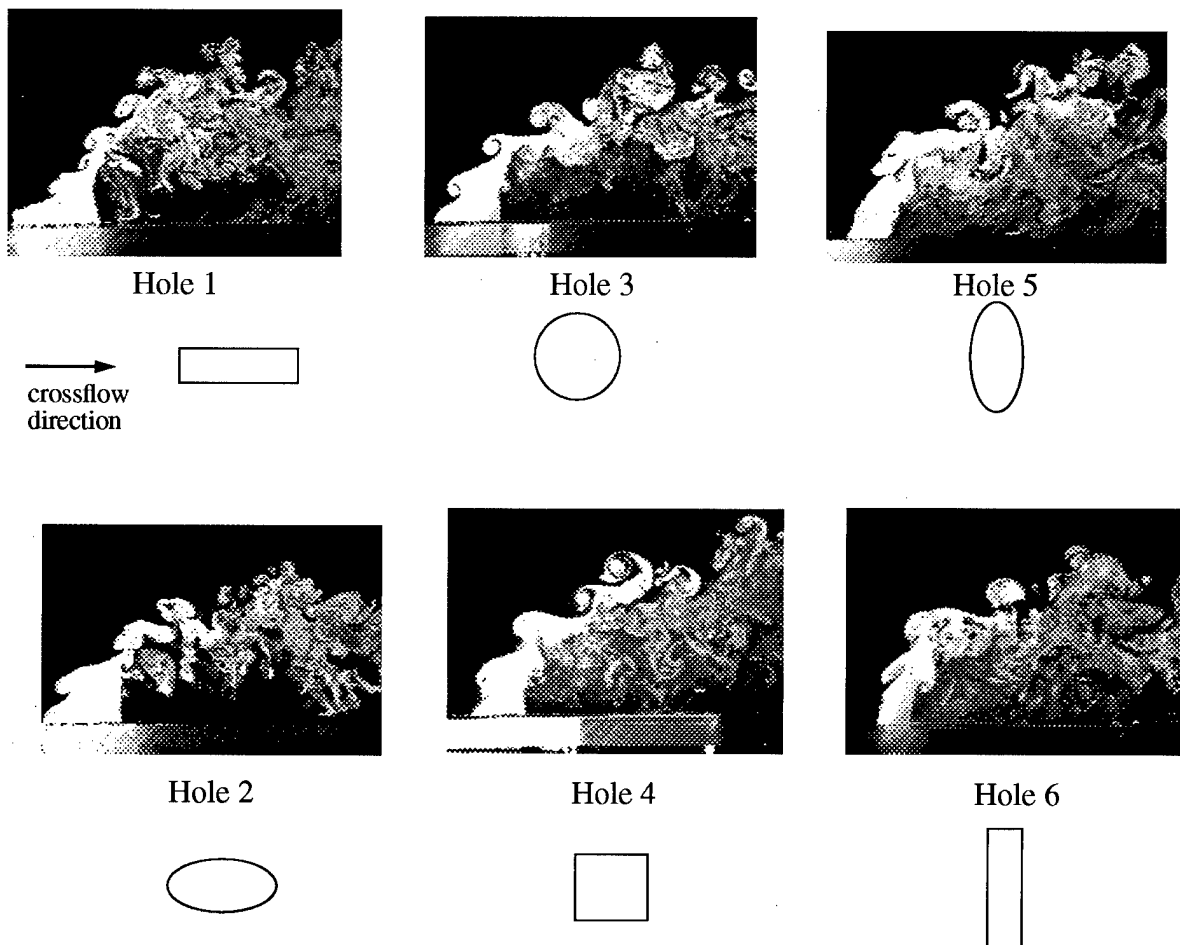


Figure 6 Jet trajectory and hole geometries

Although the width of the side wall fixes the initial separation distance between the side wall vortices, an anti-kidney pair of vortices related to the realigned vorticity also affects the jet lift-off

behavior, as discussed next.

[10-b] Double-decked vortical structure: anti-kidney pair

Figure 4 reveals that vortical structures appear to be stacked on top of one another. The lower-most vortex pair, located beneath the jet, is steady and has the same sense of rotation as the kidney-shaped vortices. Its origin is the aforementioned side-wall boundary layer; as the jet emanates from the hole, the crossflow forces the side wall boundary layer to roll up into kidney-shaped vortices.

A second vortex pair rides intermittently over the top of the steady lower pair. The origin of the upper pair is found to be the hole leading edge boundary layer, which is shed periodically from the hole and rides on top of the jet. This shed vorticity, which is initially aligned transverse to the crossflow direction, becomes realigned by the entrainment of crossflow momentum into the jet frontal interface.

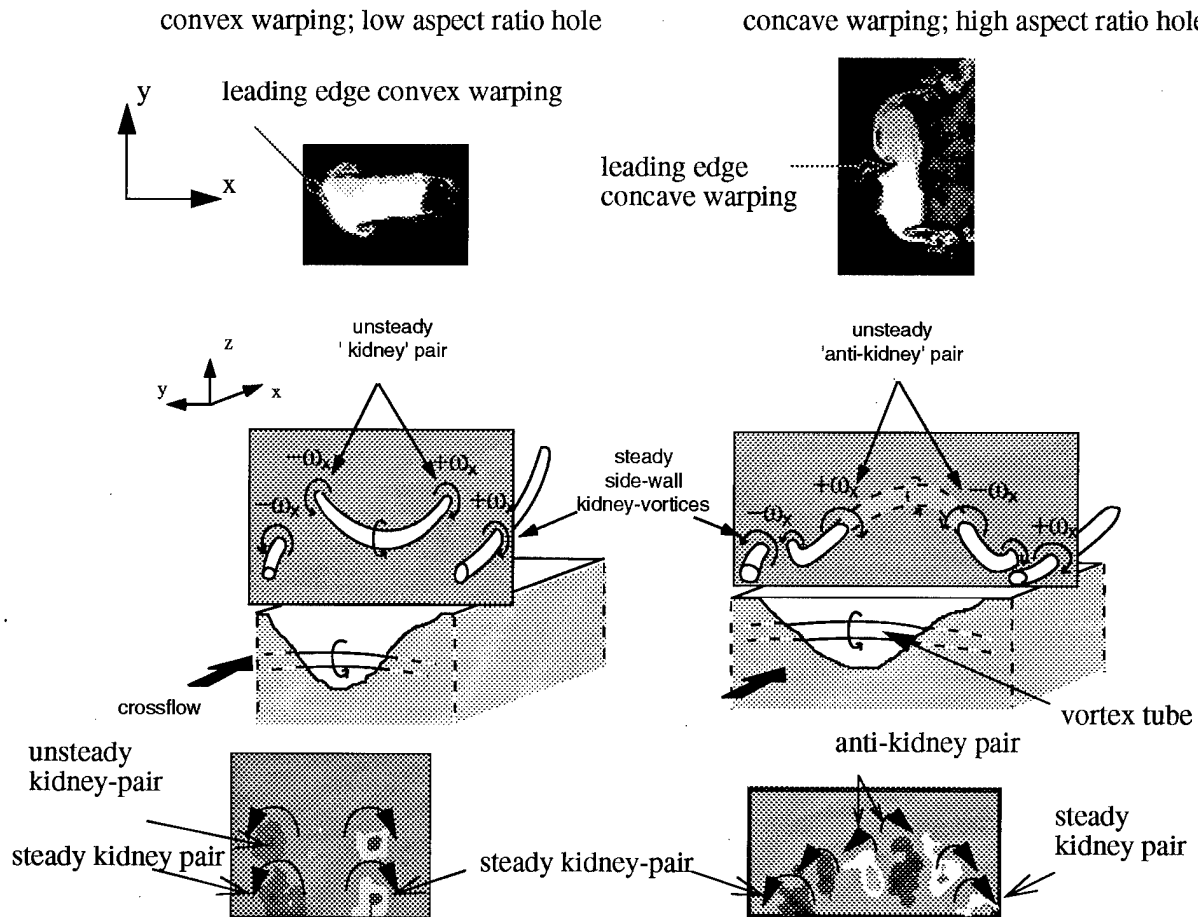


Figure 7. Unsteady positive and negative pairs

Since the entrained momentum varies from the jet center to its edge, the interface or the vortex tube warps laterally. The way how the vortex tube warps depends on the hole geometry. As shown in figure 7 (top left), for low aspect ratio holes, the warping is convex (relative to the jet), which induces an unsteady 'positive' vortex pair having the same sense of rotation as the lower steady

kidney-pair (shown schematically in middle left and as PIV result in lower left). For high aspect ratio holes, the warping is concave (top right), inducing unsteady 'negative' pair or anti-kidney pair (middle and lower right). While the 'positive' pair reinforces the steady kidney-vortices, the anti-kidney pair opposes it; the competition between them determines the jet lift-off. Likewise, the hole trailing edge boundary layer is found to play a similar, though, minor role.

These results compel a revision to the previously held view that the hole leading edge boundary layer is simply assumed to annul the one from the hole trailing edge. Here, on the contrary, all vorticity around the circumference of the jet is found to influence the downstream kidney-vortex structures.

[10-d] Implications to the holes used in industry

The acquired cognizance of the anti-kidney pair and its effect upon weakening the kidney-pair facilitated the interpretation of the performance of three industrial film cooling holes studied under separate funding (Haven et al. 'Anti-Kidney Pair of Vortices in Shaped Holes and their Influence on Film Cooling Effectiveness' to be presented at ASME Turbo Expo '97). The measured difference in film cooling effectiveness is found to be explainable by the different degree of competition between the kidney and anti-kidney pairs.

11. Personnel

Major Brenda A. Haven, a doctoral student at the University of Washington sent from the US Air Force Academy.

12. Publications/Meeting Presentation

"The Effect of Hole Geometry on the Near Field Character of Crossflow Jets", B.A. Haven, Ph.D. Thesis, Department of Aeronautics and Astronautics, University of Washington, 1996.

"The Effect of Hole Shapes on Crossflow Jets", B.A. Haven and M. Kurosaka, submitted for publication to *Journal of Fluid Mechanics*.

"Improved Jet Coverage through Vortex Cancellation", B.A. Haven and M. Kurosaka, 1996 *AIAA Journal*, vol. 34, No.11 pp.2443-2444.

"The effect of Hole Geometry on Lift-off Behavior of Coolant Jets", B.A. Haven and M. Kurosaka, AIAA Paper 96-0618.

13. Interactions/Transitions

The implications of the anti-kidney pair on industrial film cooling holes have been conveyed to GE, P & W, Allison, and Solar Gas Turbine and Wright Laboratories.

14. Honors/Awards

Major B. A. Haven received 1996 AIAA Northwest Section Outstanding student award for her PH.D. thesis work conducted under the grant.